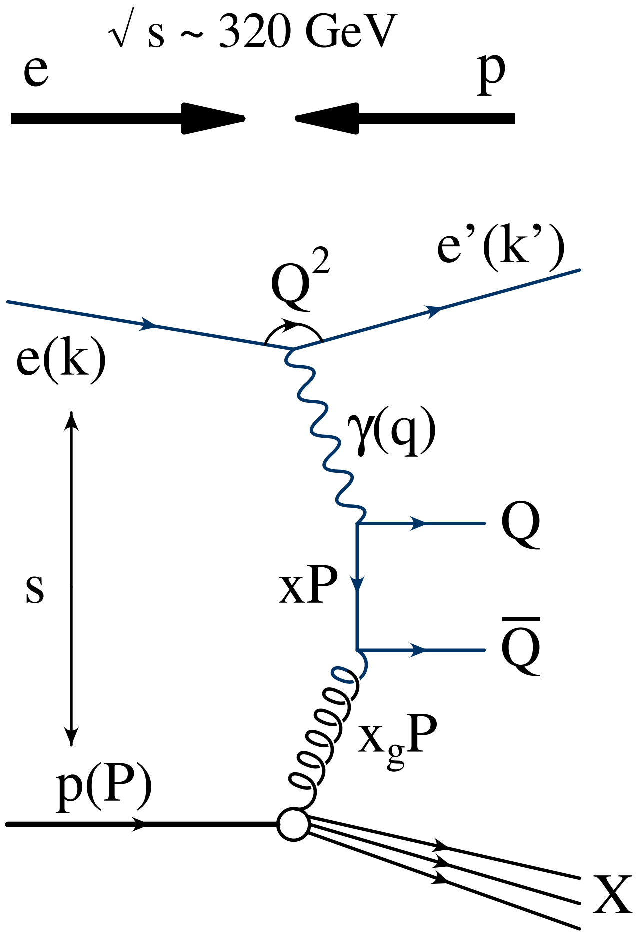
Charm Production
at H1

Outline

- Introduction
- Charm Production in DIS
- Charm Photoproduction
- Double Tags
- Charm in Diffraction
- Summary and Outlook

Heavy Quark Production Kinematics

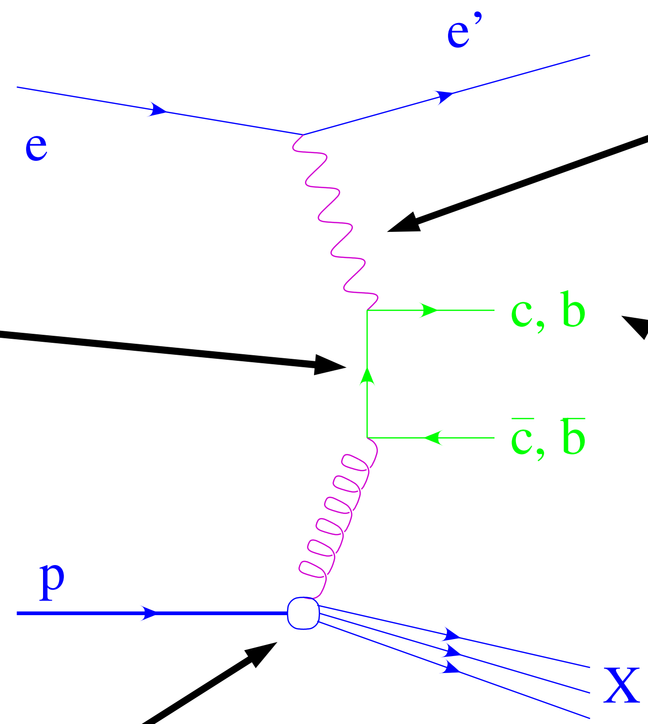


- two kinematical regions
  - photon almost on mass shell ($Q^2 \rightarrow 0$)
    - photoproduction (PHP)
  - photon highly virtual ($Q^2 > 1 GeV^2$)
    - deep inelastic scattering (DIS)

- same production mechanism (photon gluon fusion) but real photons can behave as hadrons

Heavy Quark Production Probing QCD

factorization: p structure ⊗ pQCD ⊗ γ structure ⊗ fragmentation



γ structure
- charm excitation

perturbative QCD
- multiple scales (m_Q, p_t, Q^2, ...)

fragmentation
- universality

proton structure
- structure functions
- parton densities
- evolution models (DGLAP, BFKL, CCFM)

Heavy Quark Production

- test perturbative QCD
- study structure of
  - proton (in particular gluon content)
  - photon
- study fragmentation, hadronization, ...

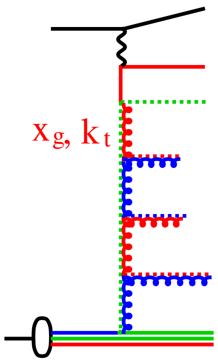
- cross sections at HERA are large

  $\sigma(e\ p \longrightarrow c\ X) \sim O(1\ \mu b)$
- but
  - acceptance, trigger, ...
- visible cross sections are small

  $\sigma_{vis} \sim O(10\ nb)$

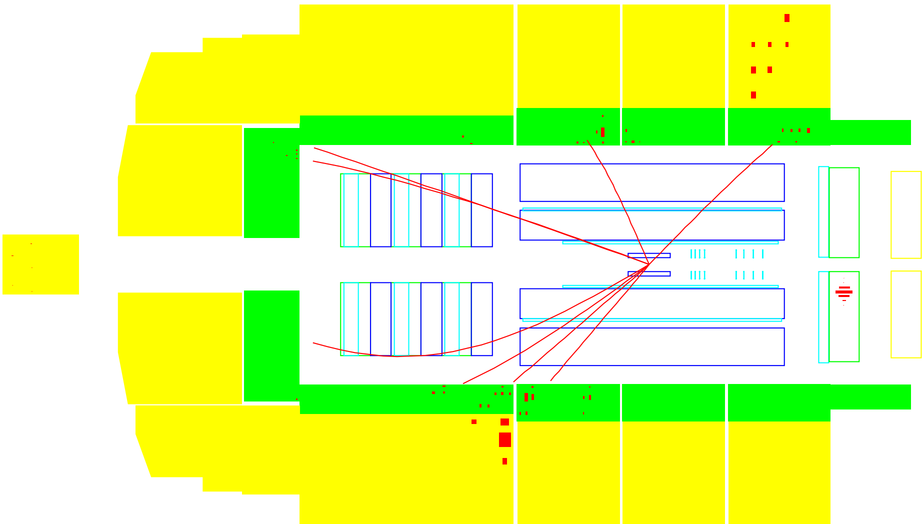
Modelling Heavy Quark Production

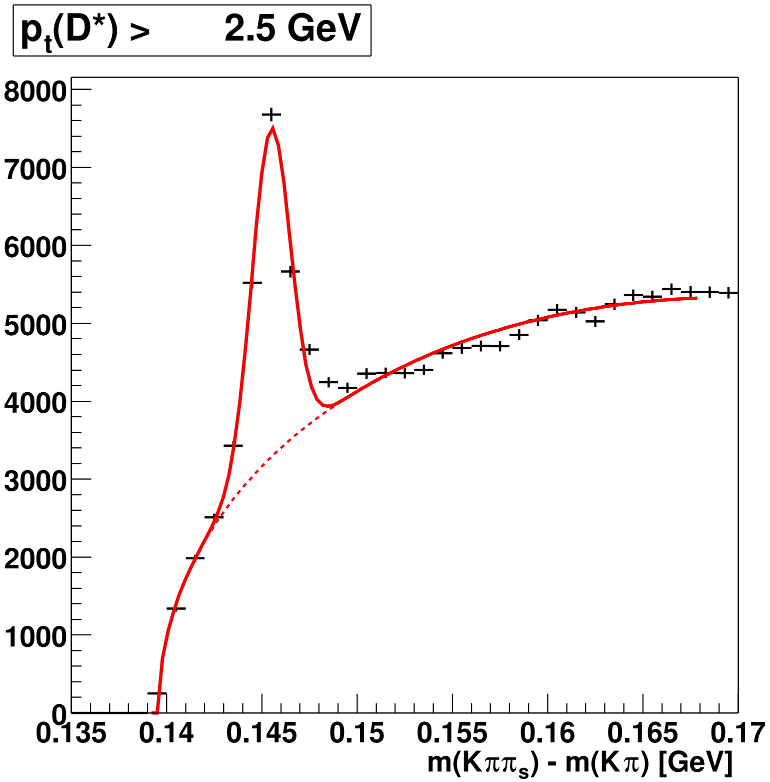
- pQCD calculations in NLO (DGLAP evolution)
  - fixed (NLO) order (FO) calculations (“massive”)
    - HQ mostly via BGF (quark masses taken into account)
    - valid for Q, $p_t \approx m_Q$
  - resummed (RS) calculations (“massless”)
    - HQ part of parton densities (massless quarks)
    - resum contributions of large logarithms (Q/m_Q, p_t/m_Q)
    - valid for Q, $p_t \gg m_Q$
  - matched calculations (FONLL)
    - merge FO and RS calculations
- MC generators (LO matrix elements + parton showers)
  - AROMA: direct only, DGLAP evolution
  - HERWIG, PYTHIA, RAPGAP: direct + resolved, DGLAP
  - CASCADE: direct, CCFM like evolution
  - CCFM (wrt DGLAP)
    - no ordering in k_t required
    - gluon density and hard cross section k_t dependent
    - evolution phase space larger



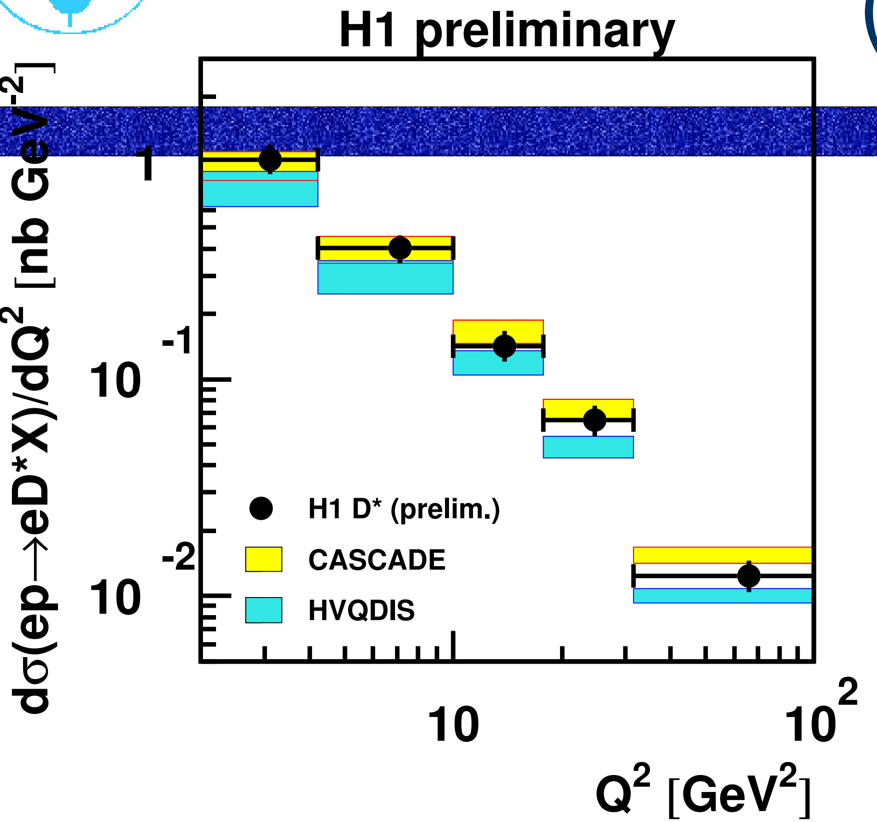
Charm Tagging

- mass difference method, e.g.
  $\Delta M = M(K^-\pi^+\pi^+) - M(K^-\pi^+)$

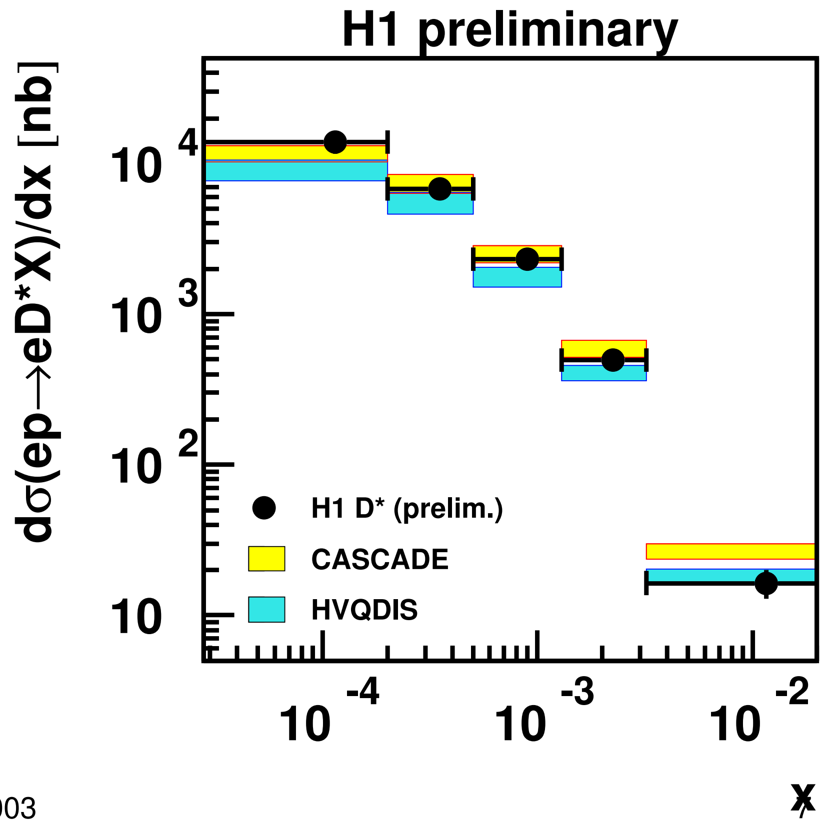




Differential Cross Sections (DIS)

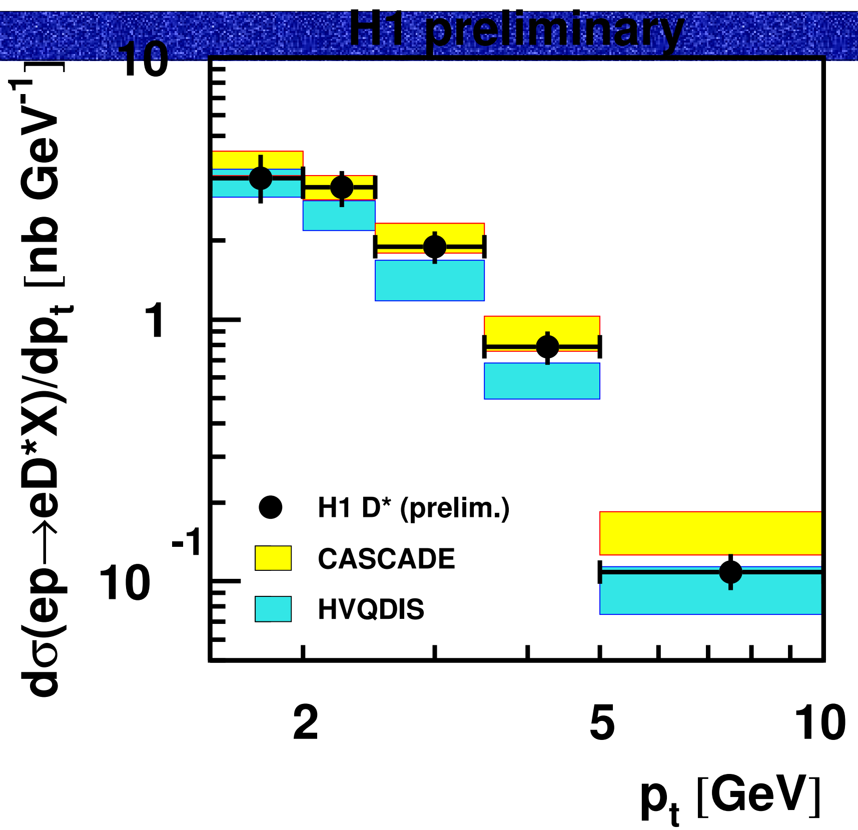


$2 < Q^2 < 100$ GeV^2
$0.05 < y < 0.7$
$1.5 < p_t(D^*) < 15$ GeV
$|\eta(D^*)| < 1.5$



- theoretical uncertainties due to charm quark mass and fragmentation
- measured cross section larger than NLO calculation (HVQDIS), shape okay
- measured cross section agrees better with CCFM model (CASCADE)

Differential Cross sections (DIS)



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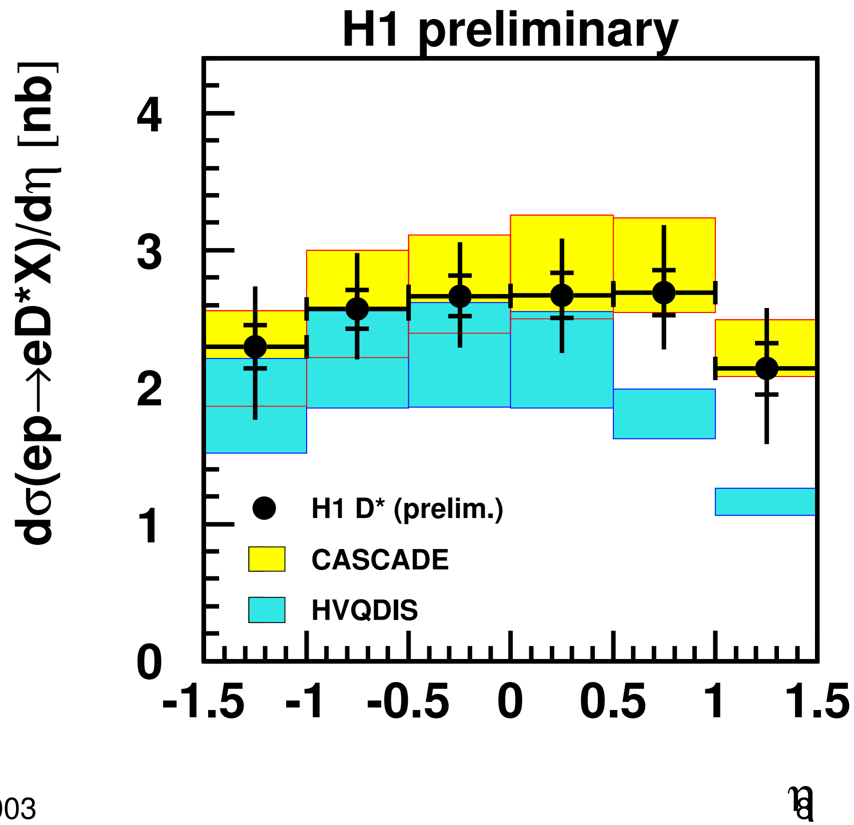
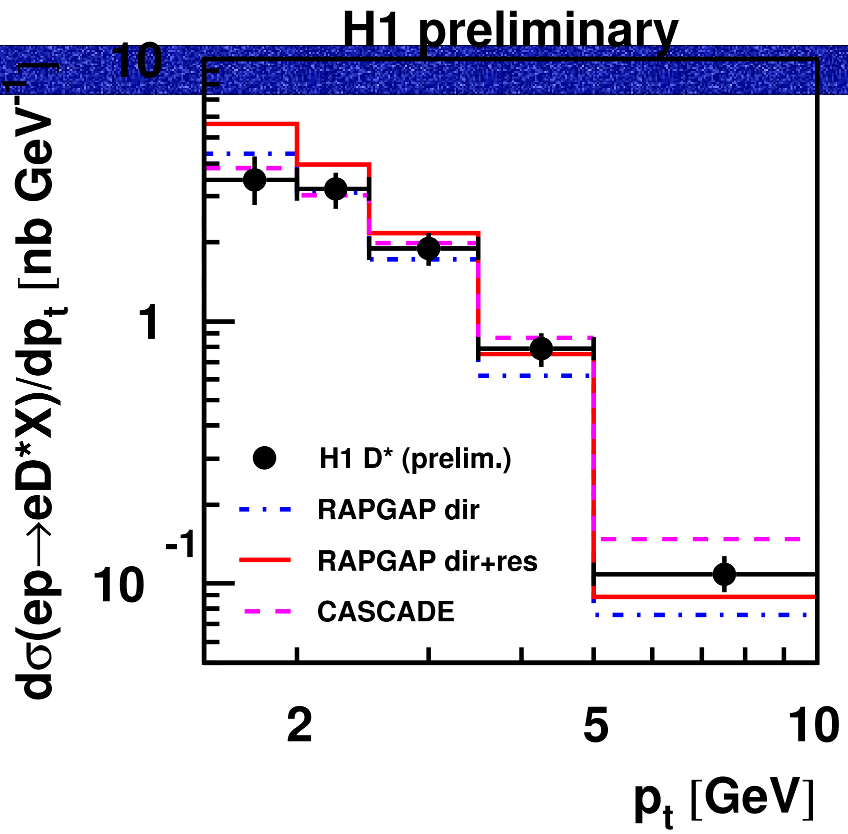


- HVQDIS: reasonable agreement, execpt in forward region
- CASCADE: better agreement with data

Differential Cross sections (DIS)



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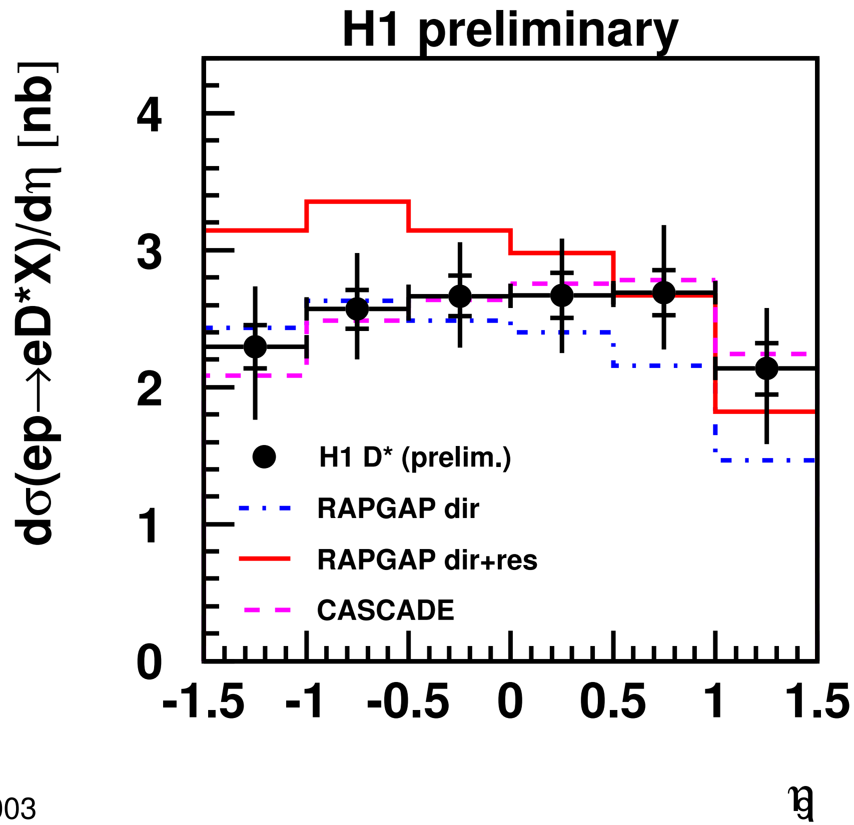
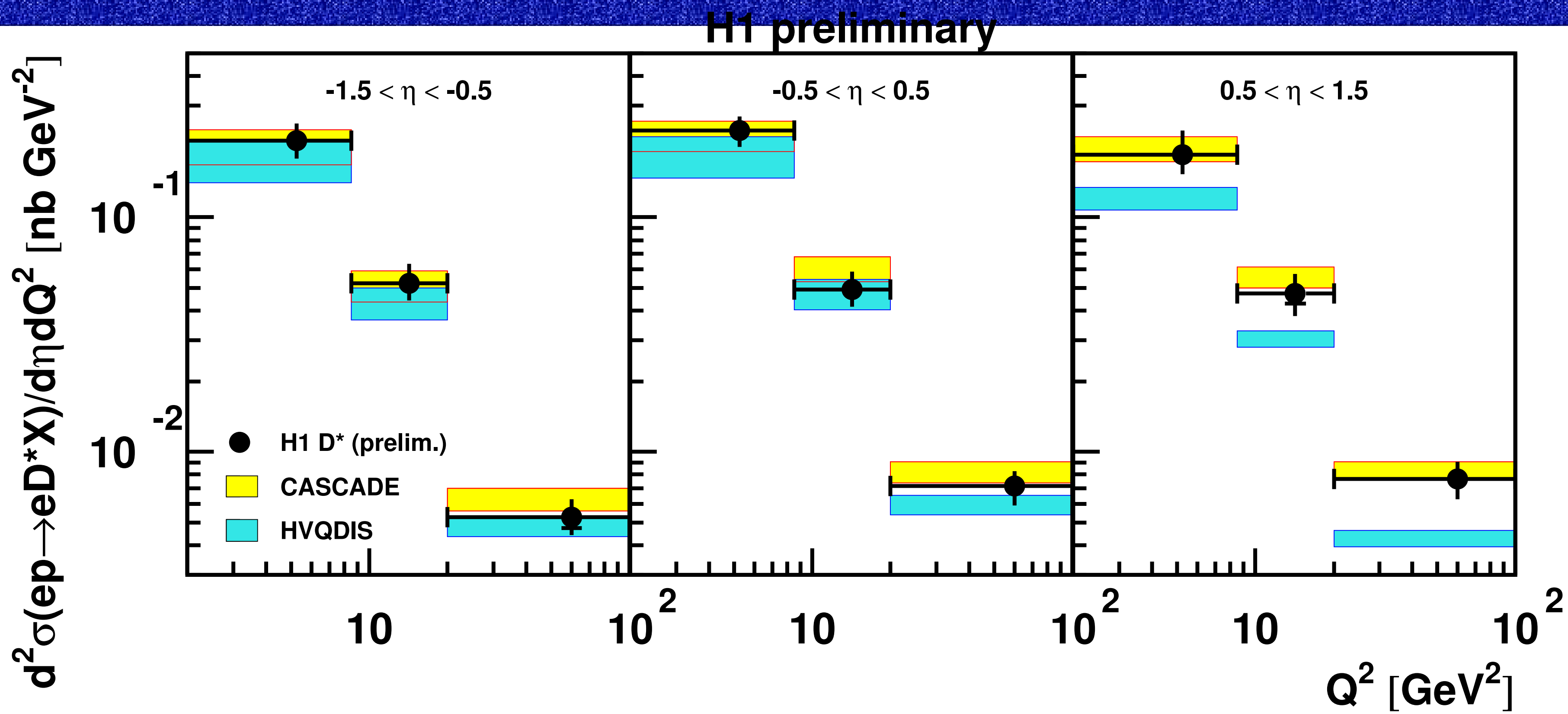


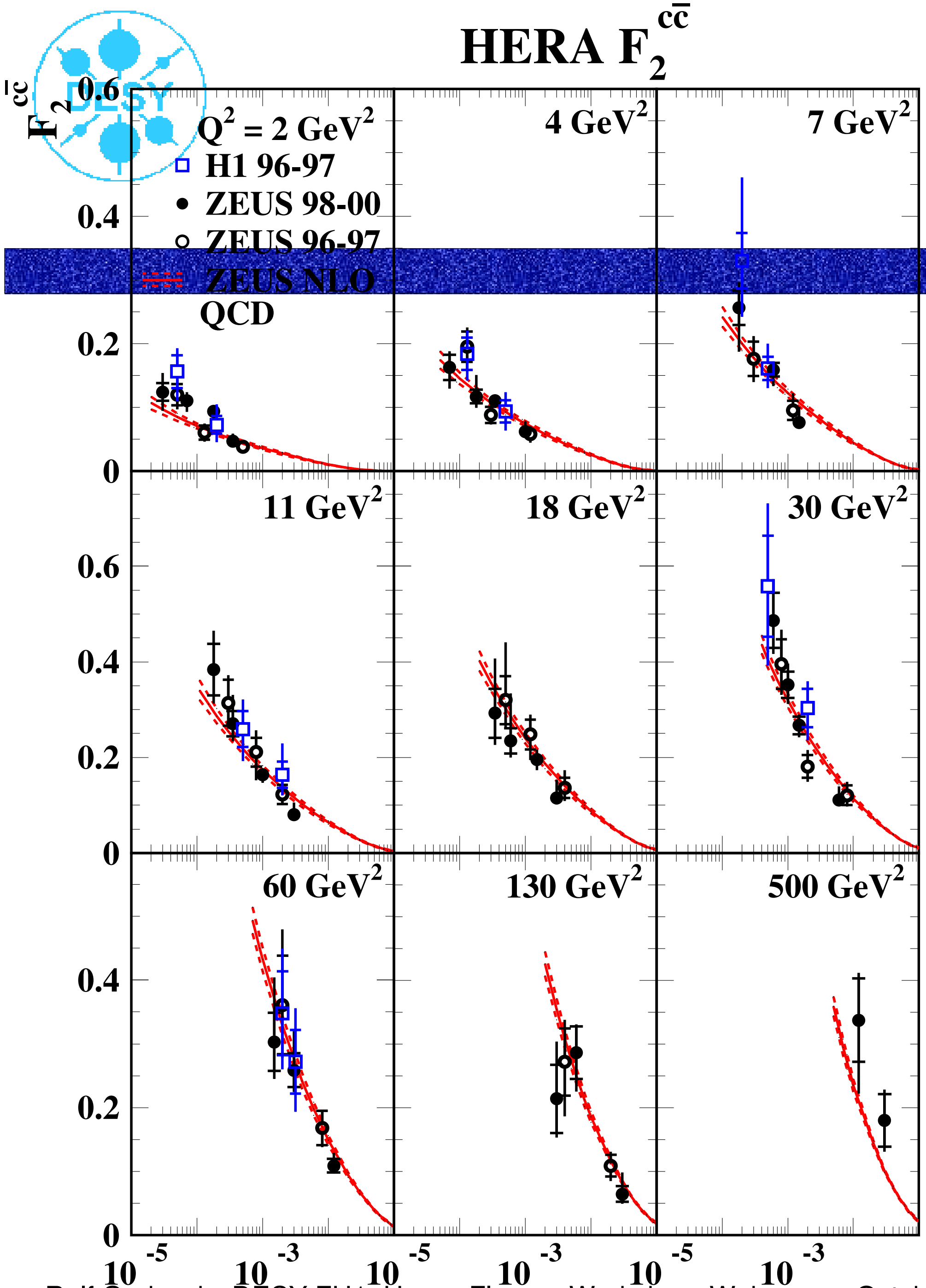
- RAPGAP with direct processes only slightly below data
- RAPGAP with resolved contribution taken into account considerably above data

Double Differential Cross sections (DIS)



$2 < Q^2 < 100$ GeV^2
$0.05 < y < 0.7$
$1.5 < p_t(D^*) < 15$ GeV
$|\eta(D^*)| < 1.5$

- HVQDIS: excess independent of Q2 and concentrated on low pT
- CASCADE: reasonable agreement with data

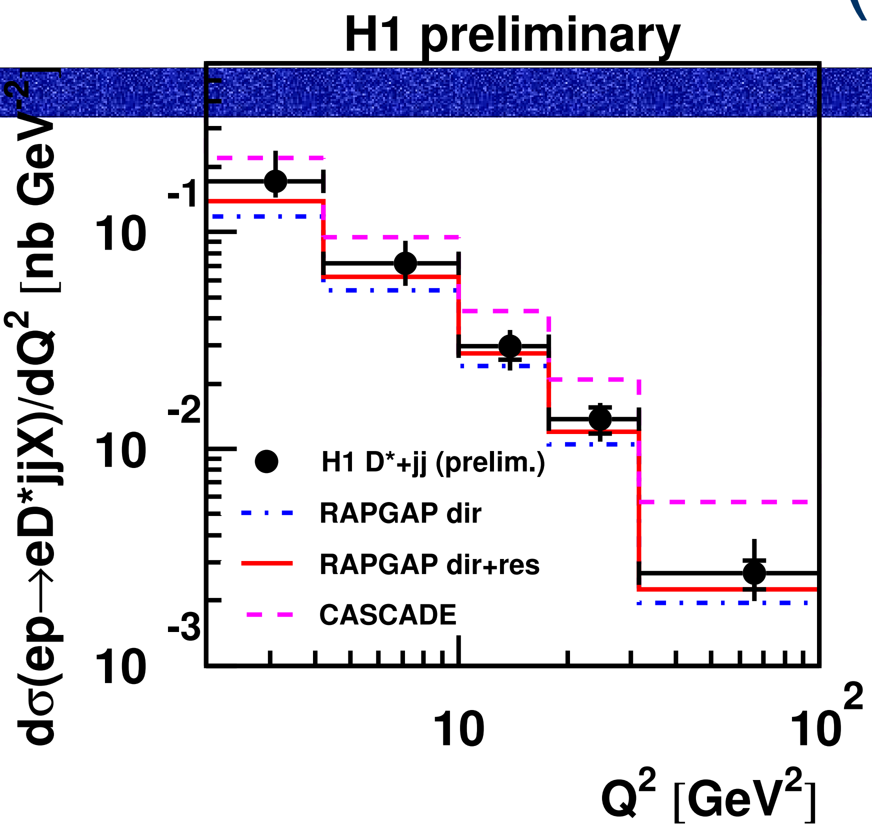


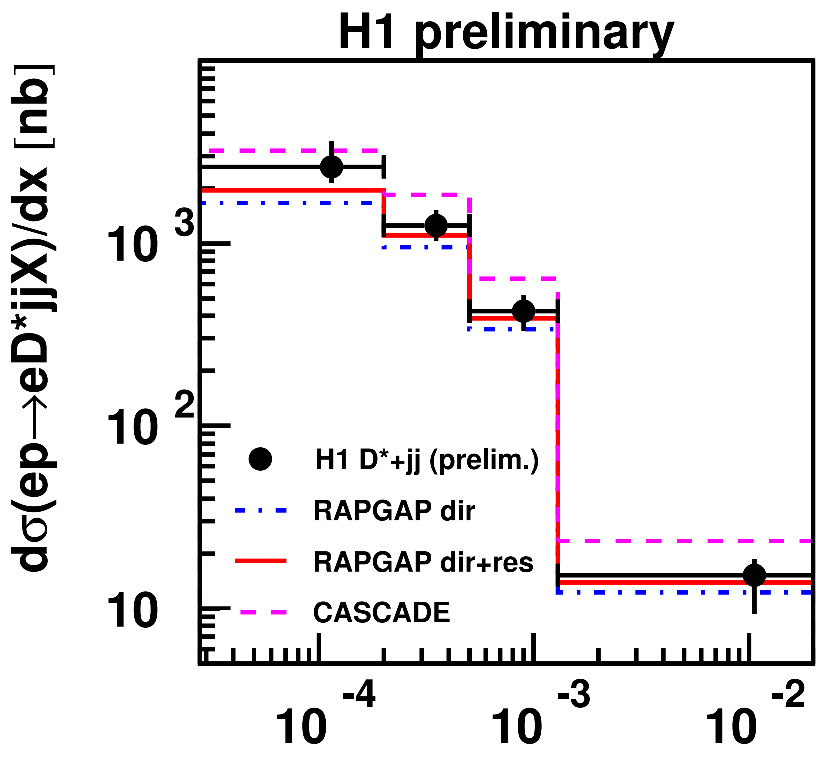
F_2^c

- measure D* cross sectionn in restricted kinematic range
  - model dependent extrapolation
- agreement between H1 and ZEUS measurements
- agreement with ZEUS NLO QCD fit over wide range in Q^2 and x
- prediction of charm contribution to F_2 from scaling violations consistent with F_2^c measurement

D* + Jets (DIS)

2 < Q^2 < 100 GeV^2
0.05 < y < 0.7
1.5 < $p_t(D^*)$ < 15 GeV
$|\eta(D^*)|$ < 1.5
E_t(jet1) > 4 GeV
E_t(jet2) > 3 GeV
-1 < η(jet1,2) < 2.5





- CASCADE above data (different from inclusive D* measurement)
- direct RAPGAP below data
- direct + resolved RAPGAP closer to data

D* + Jets (DIS)

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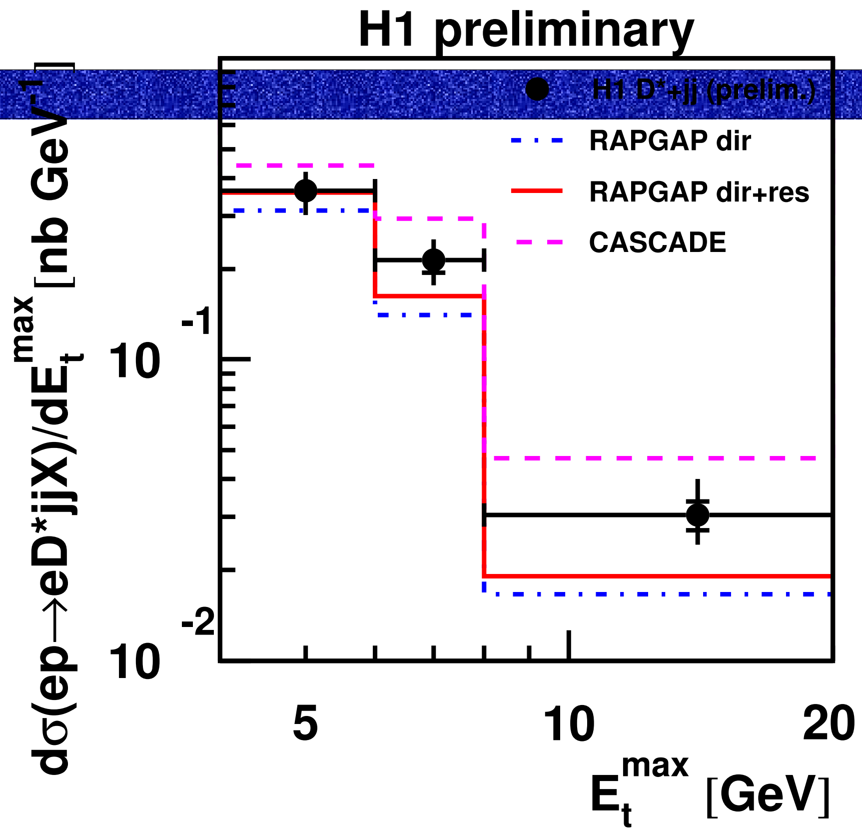
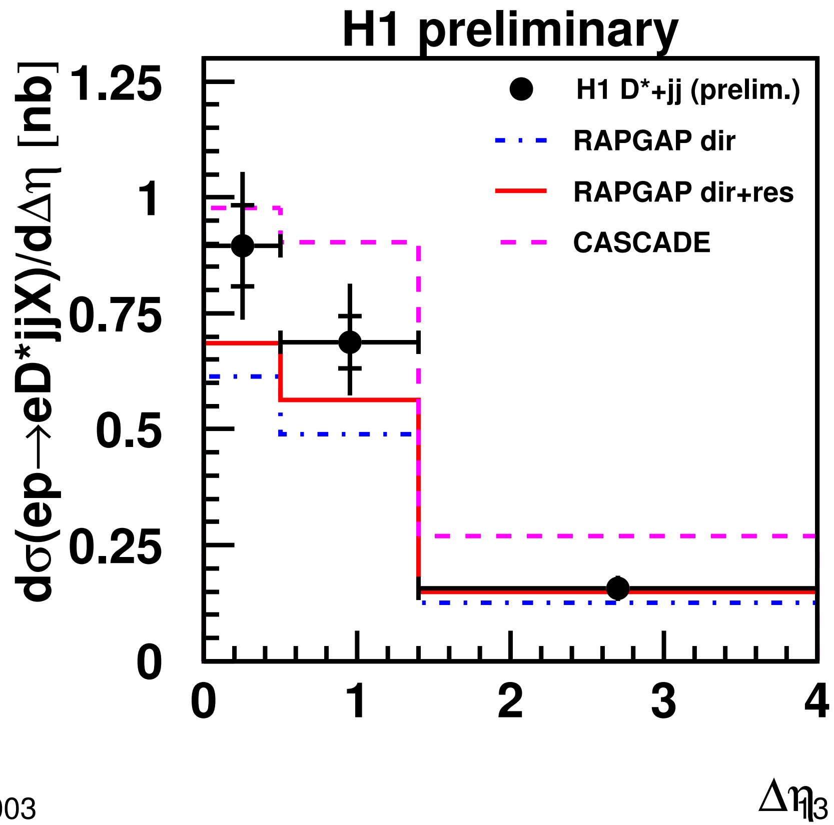


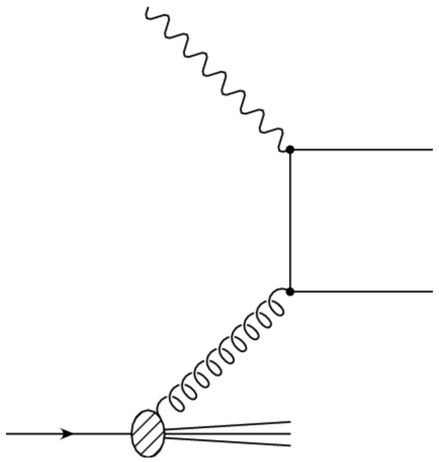


- CASCADE above data (different from inclusive D* measurement)
- direct RAPGAP below data
- direct + resolved RAPGAP closer to data

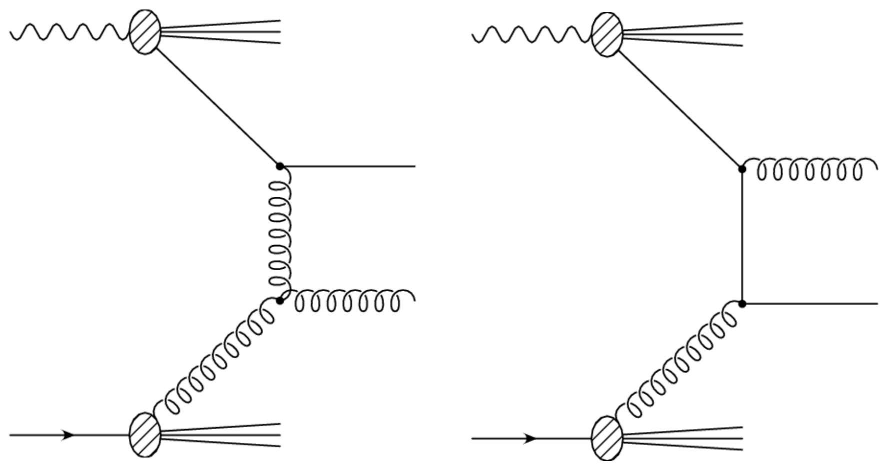
Charm Photoproduction

- quasi-real photons exhibit hadronic behaviour

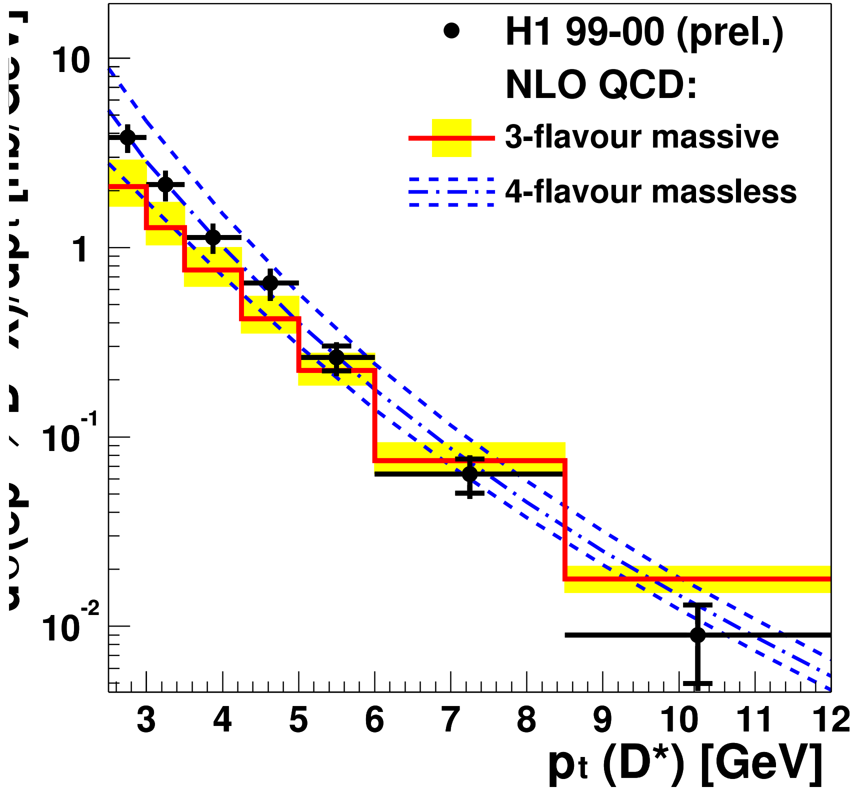
direct



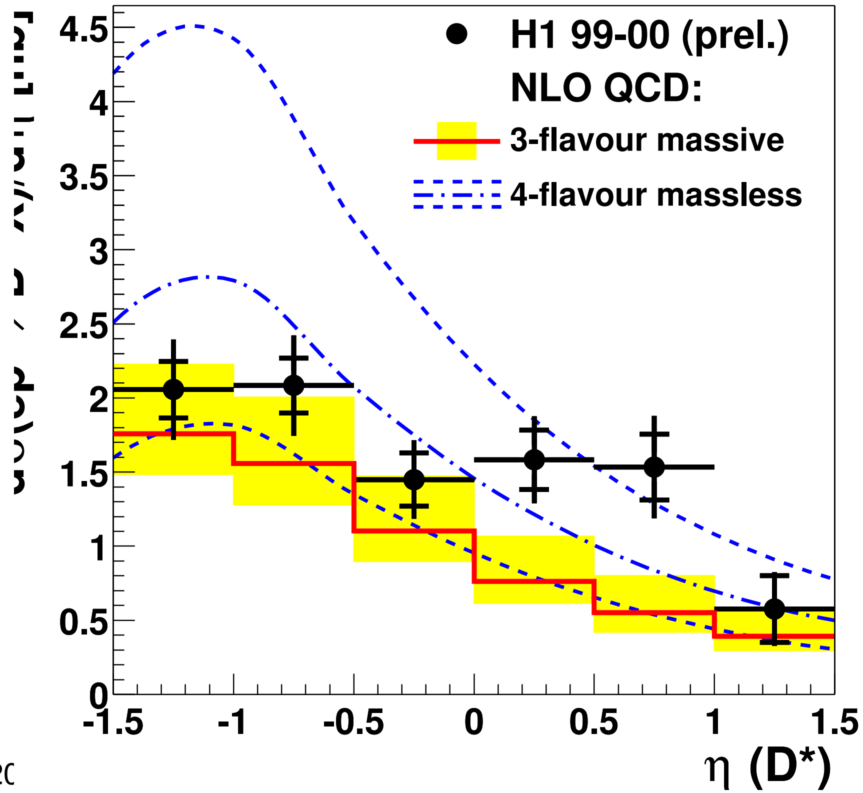
charm excitation



Differential Cross sections (PHP)



$Q^2 < 0.01$ GeV^2
$171 < W < 256$ GeV
$p_t(D^*) > 2.5$ GeV
$|\eta(D^*)| < 1.5$



- theoretical uncertainties due renormalization and factorization scales
- " 3 flavour massive" below data (at low p_t)
- " 4 flavour massless" reasonable agreement
- enhancement in forward region

Differential Cross sections (PHP)

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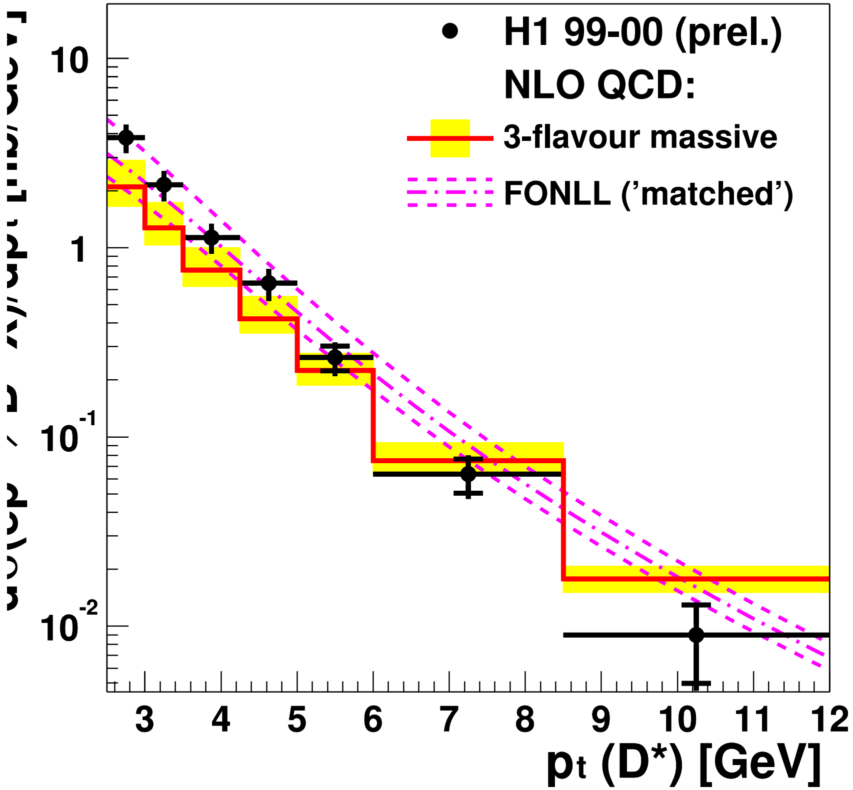
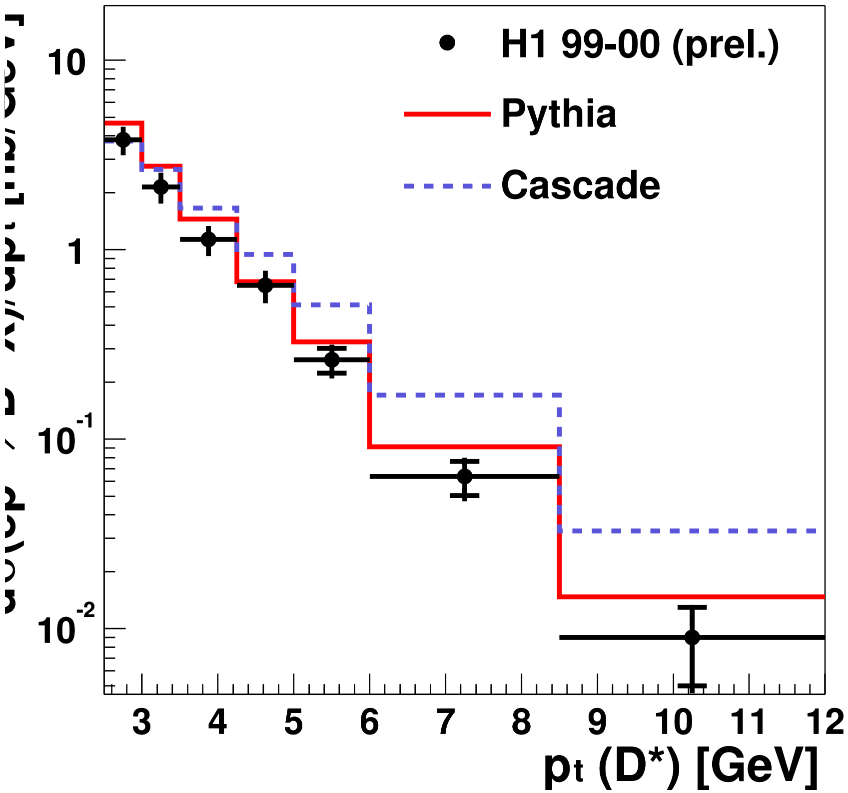


- comparison with FONLL
  - dotted curve: central prediction
  - solid curve: all uncertainties added linearly
  - dashed curve: without factorization scale uncertainties
- FONLL closer to data in low p_t region than "3 flavour massive"

Differential Cross sections (PHP)



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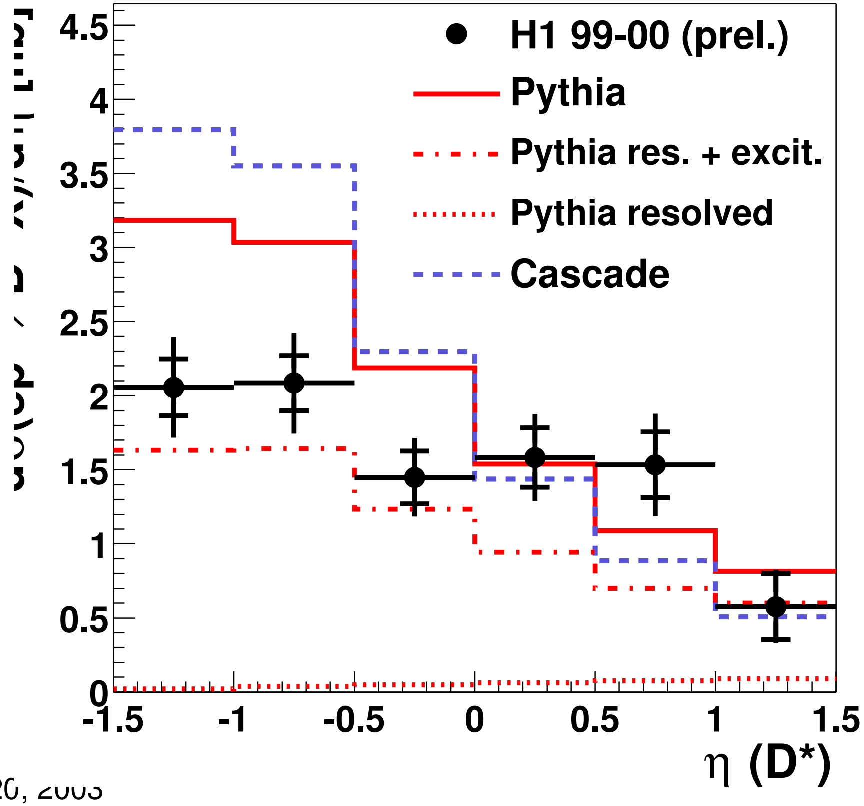
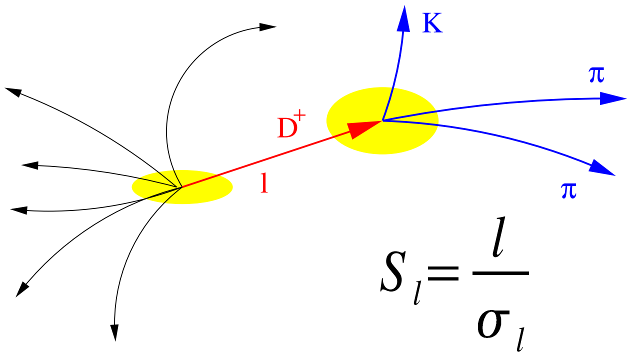


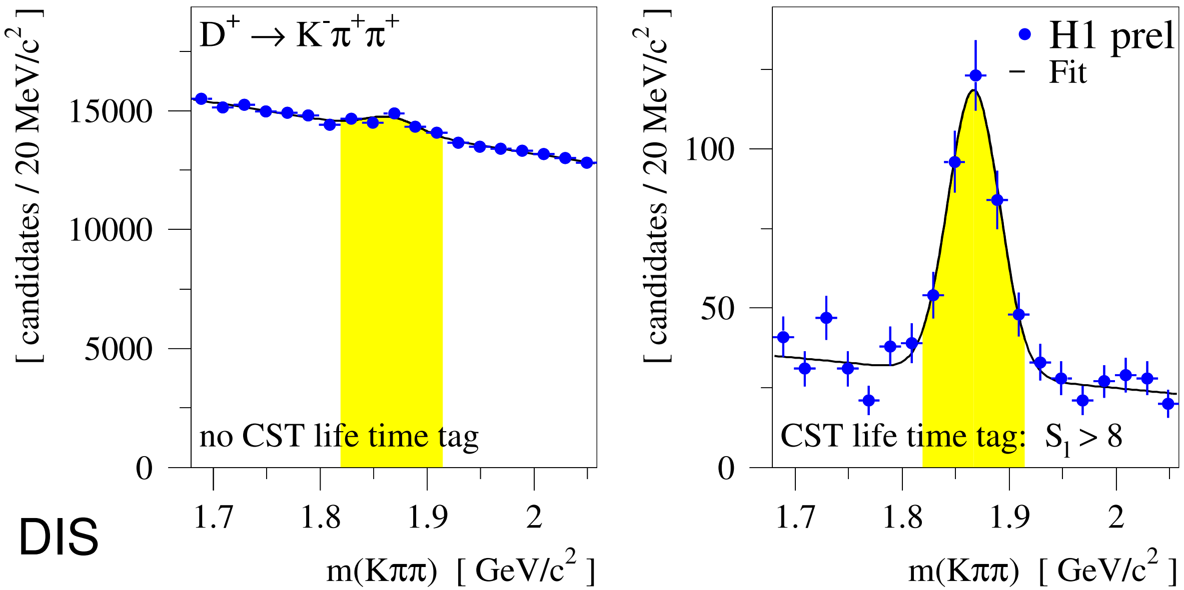
- PYTHIA: slightly above data, p_t distribution okay, charm excitation important
- CASCADE: p_t distribution too hard
- both MC models cannot describe η distribution

Charm Tagging revisited

- vertex tagging (silicon vertex detector)
- study production of various charm hadrons (D^{*+}, D^{+}, D^{0}, D_s^{+}, (Λ_c))
  - independent cross section measurements
  - fragmentation fractions

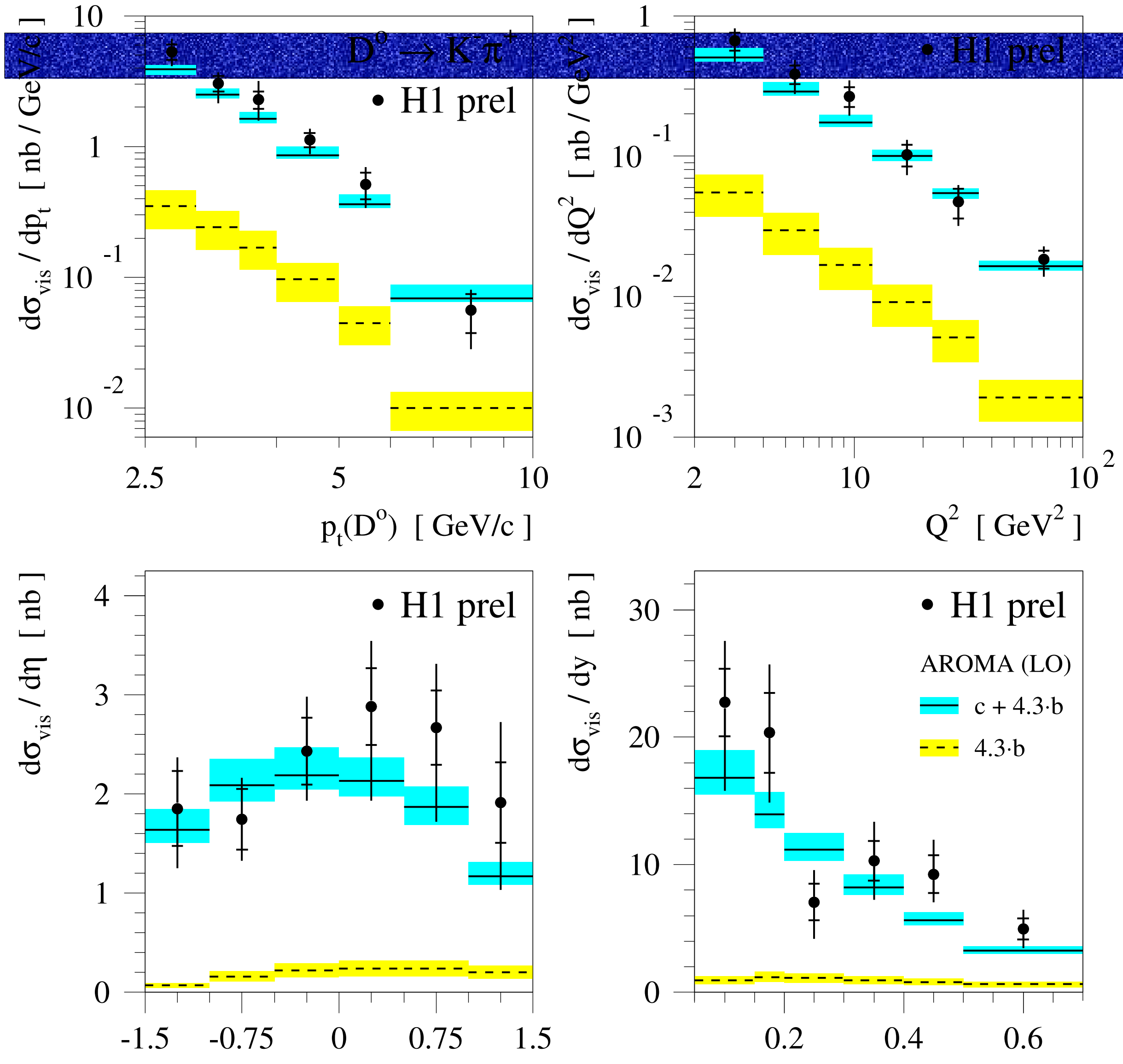


$$S_l = \frac{l}{\sigma_l}$$

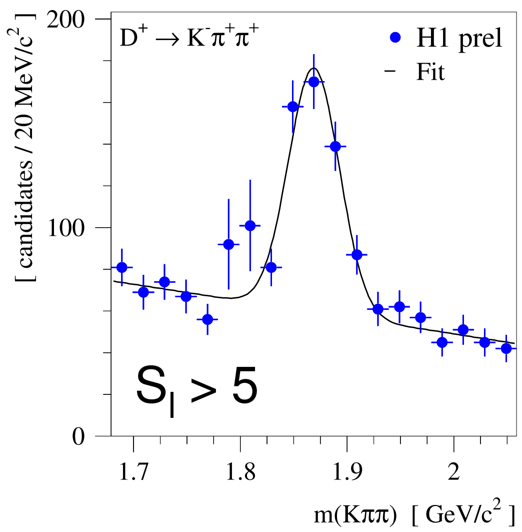


... an example: D^+ production in DIS

D^+ Production (DIS)

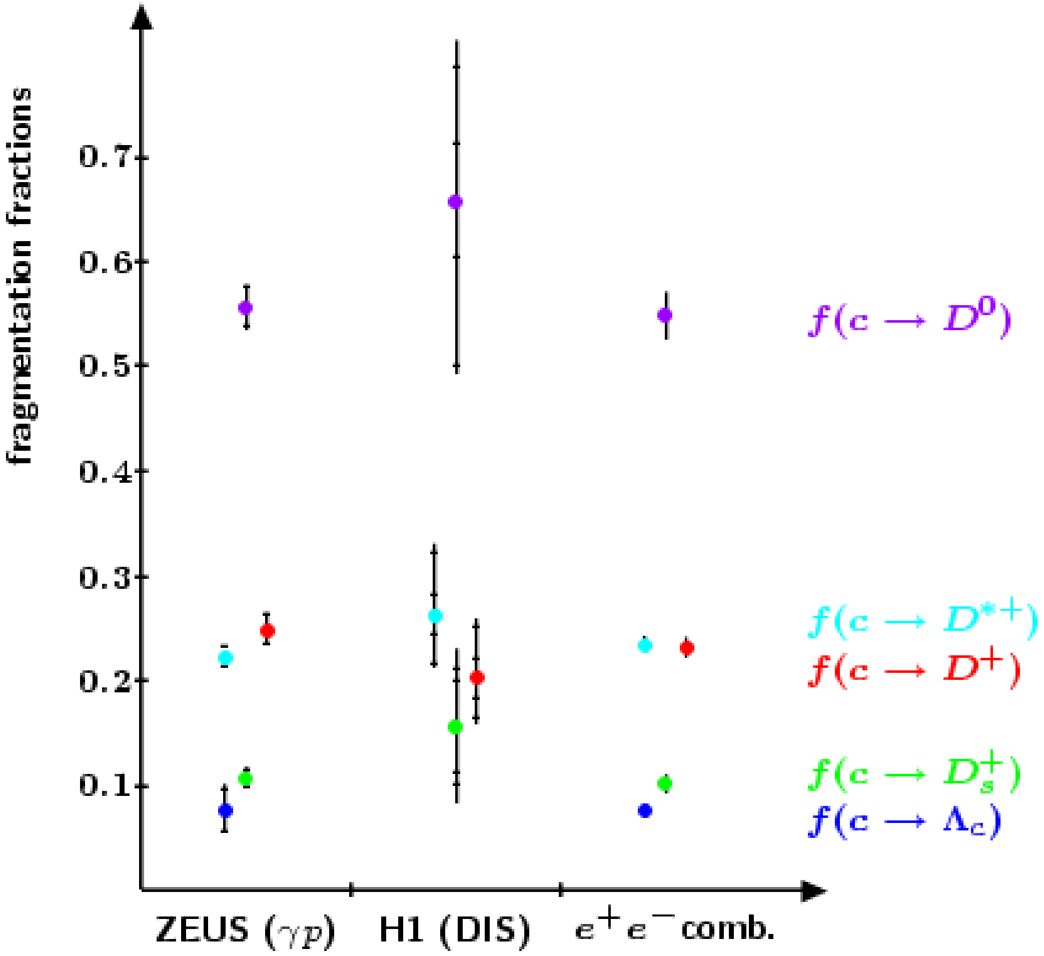


$2 < Q^2 < 100$ GeV^2
$0.05 < y < 0.7$
$p_t(D^+) > 2.5$ GeV
$|\eta(D^+)| < 1.5$



- good agreement with LO + PS prediction (AROMA) both in shape and magnituted
- similar for D^0, D_s

Fragmentation Ratios



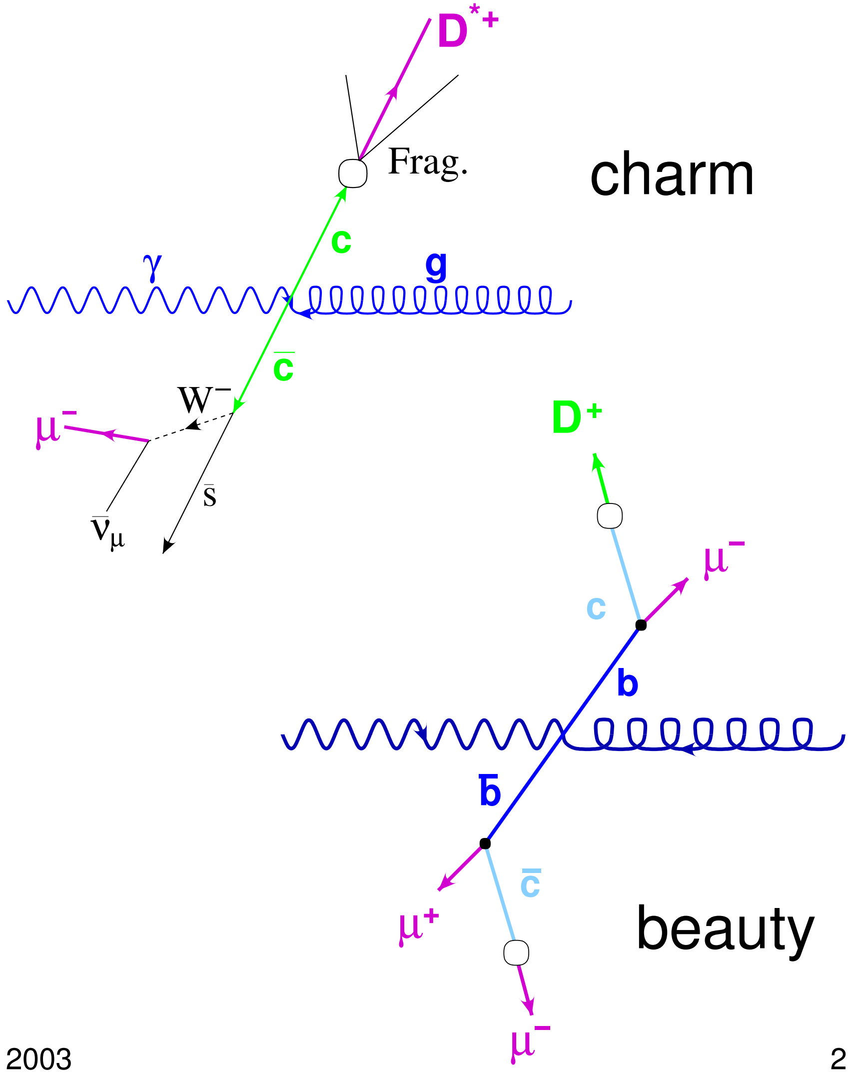
- reconstruct all charm states
- consistent with measurements in e^+e^-, ..

⇒ consistent with charm fragmentation universality

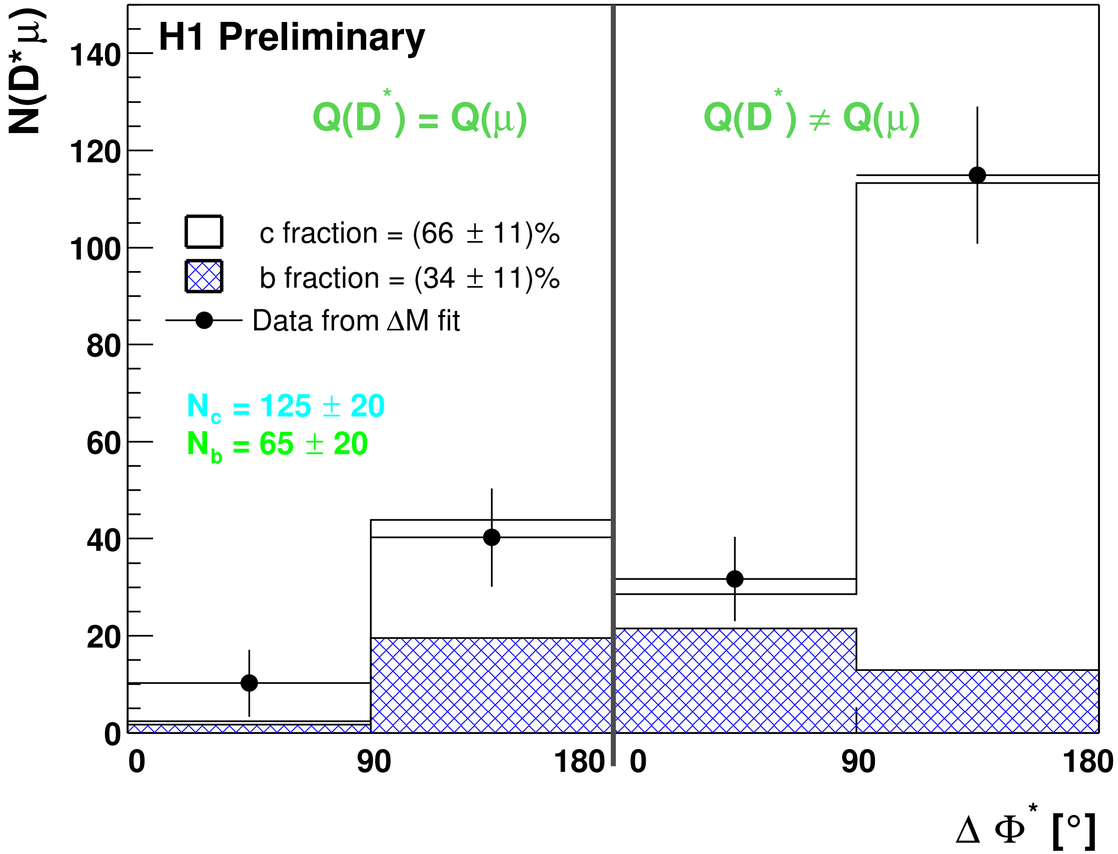
Double Tags

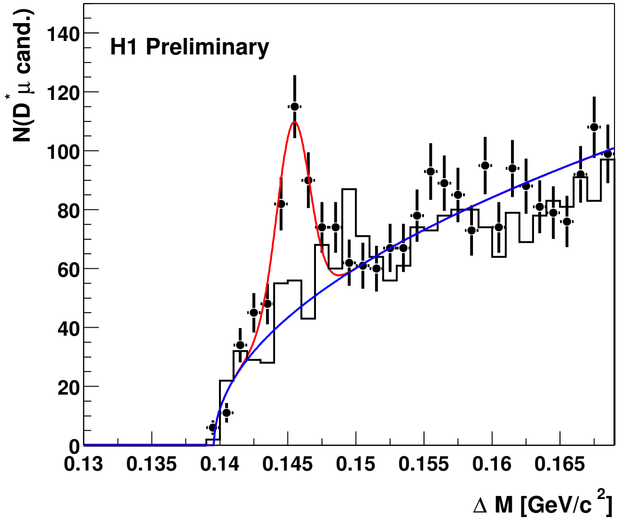
- tag both charm (beauty) quarks to completely reconstruct the hadronic final state, e.g.
  - $D^{*\pm} l^{\mp}$, $D^{*+} D^{*-}$, $l^+ l^-$, $l = e, \mu$
  - measurement of the gluon density
  - sensitivity to higher orders and non-perturbative effects

- example: $D^{*\pm} \mu^{\mp}$ analysis
  - exploit charge and angular correlations to separate charm and beauty
  - LO:
    - $\Delta\Phi = \pi$
    - $\Sigma p_t = 0$
    - $\Sigma Q = 0$
  - smearing due to higher orders and fragmentation



D*μ Double Tags



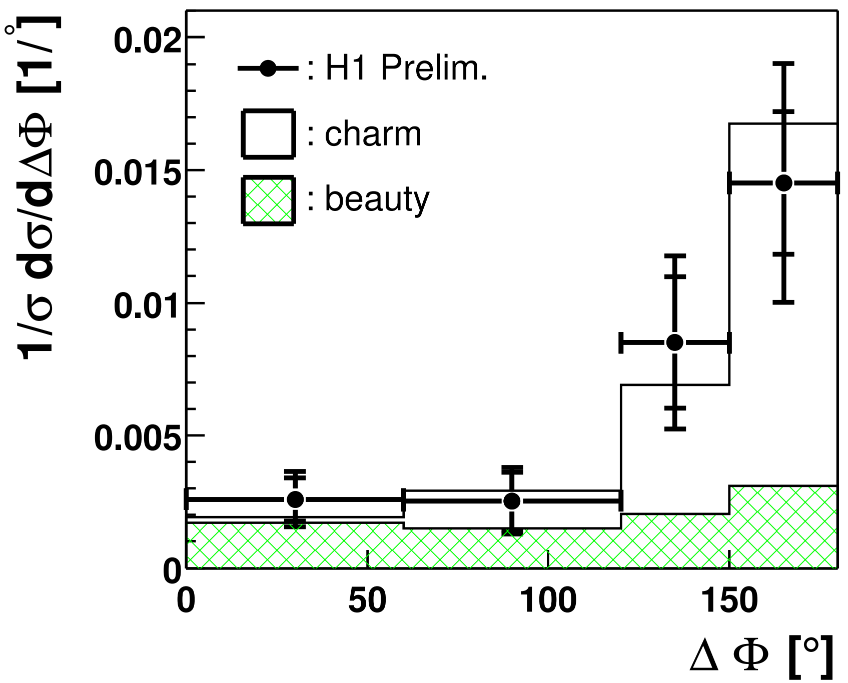


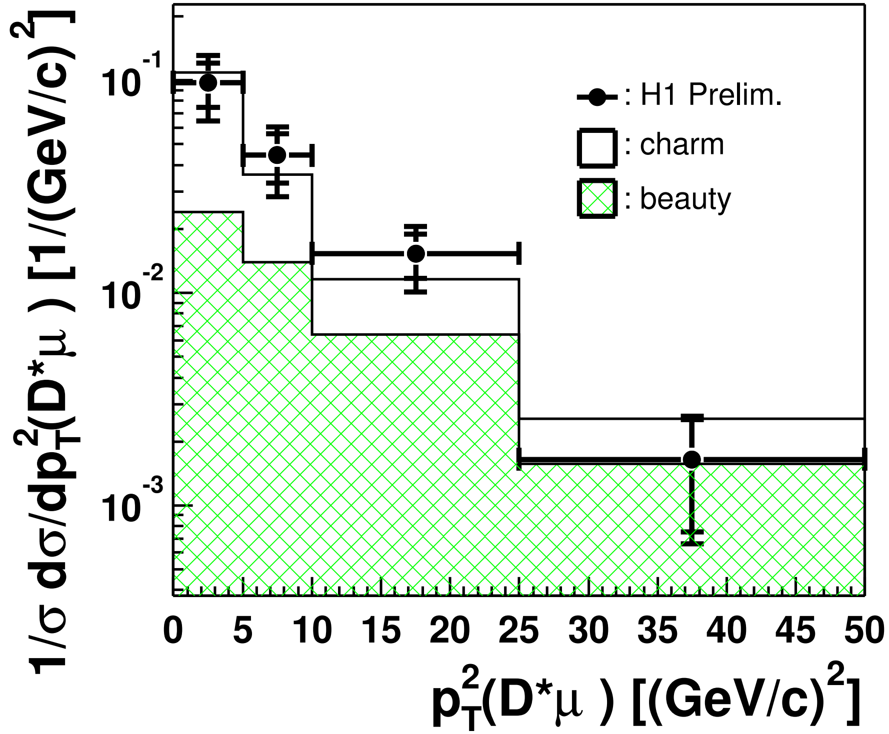
- measurement of total cross sections compatible with previous results

$p_t(D^*) > 2.5$ GeV
$|\eta(D^*)| < 1.5$
$p_t(\mu) > 1.$ GeV
$|\eta(\mu)| < 1.74$
$0.05 < y < 0.7$

D*μ Double Tags

$p_t(D^*) > 2.5$ GeV
$|\eta(D^*)| < 1.5$
$p_t(\mu) > 1.$ GeV
$|\eta(\mu)| < 1.74$
$0.05 < y < 0.7$

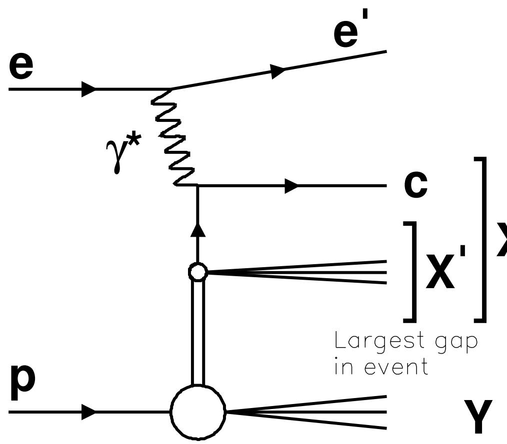


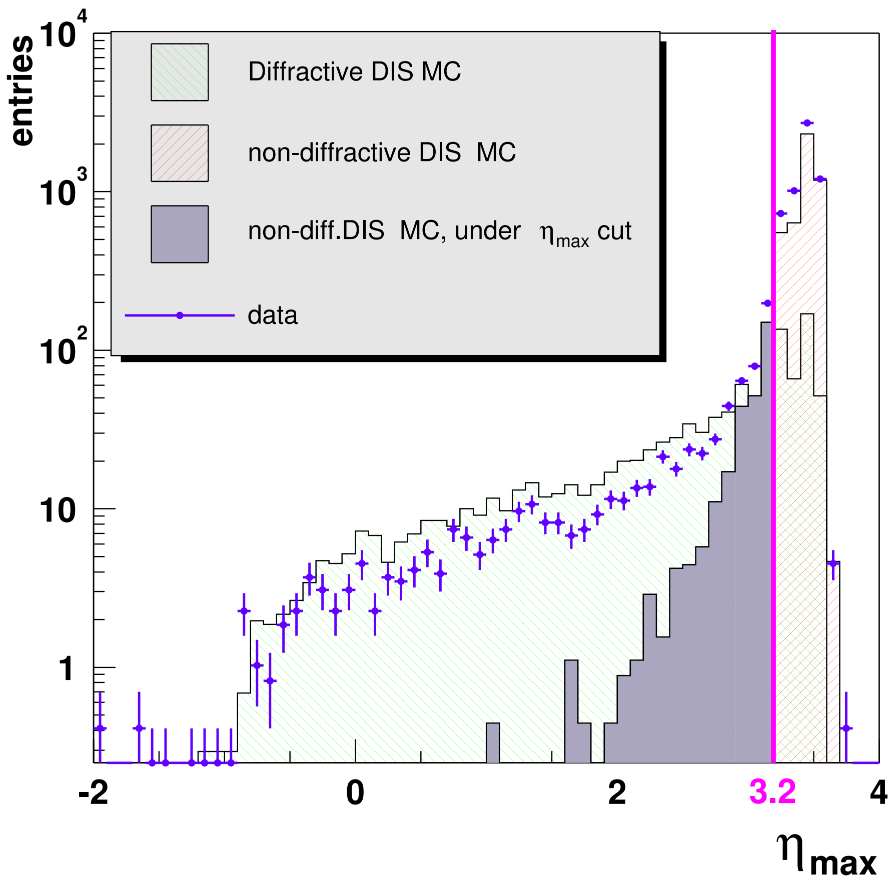


- good agreement with LO+PS prediction
- large potential for HERA II

Charm in Diffraction

- rapidity gap events
  - attributed to diffractive or pomeron exchange
- investigate partonic nature of diffraction, using the photon as a probe
- production of open charm sensitive to gluon content
- test perturbative QCD based models of diffraction





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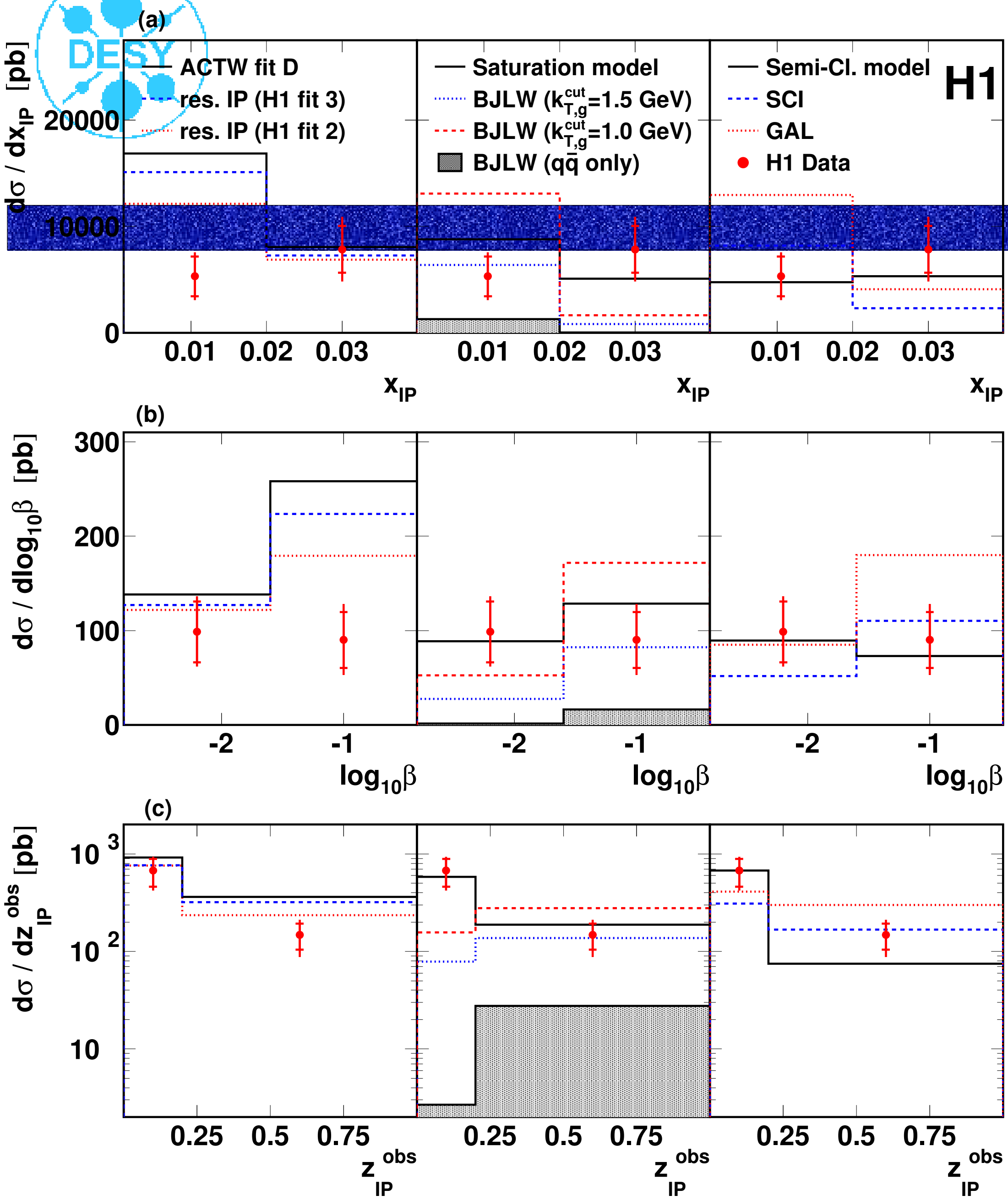
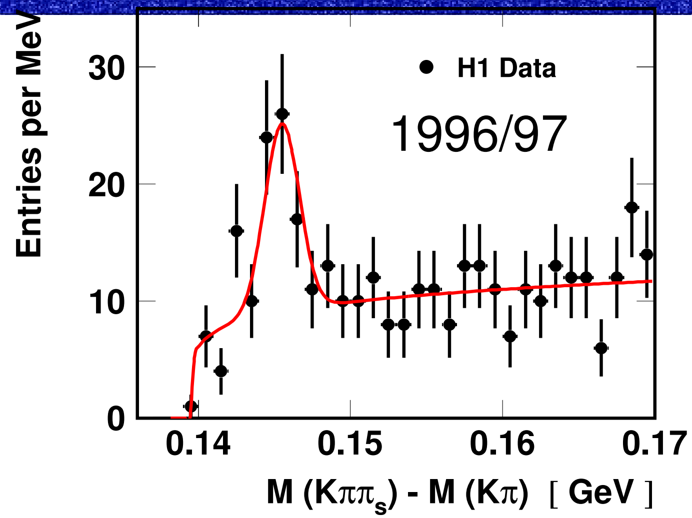
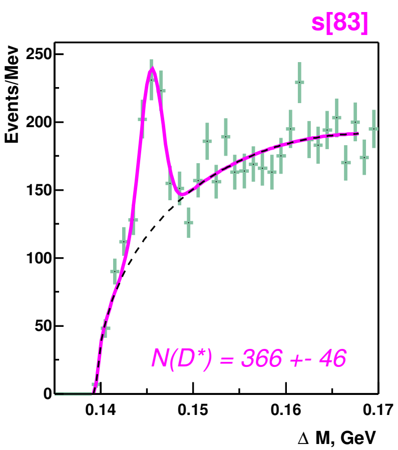


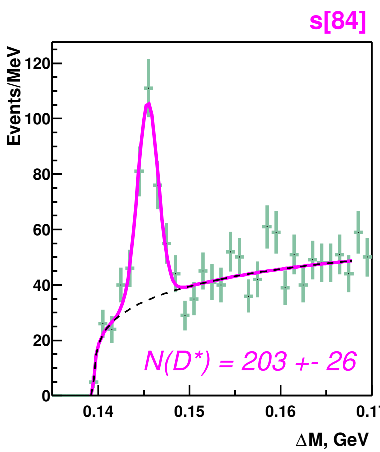
- 60% of charm production at low $z_{IP} < 0.2$, where BGF contribution is expected to dominate
- discrepancy between resolved pomeron model and data at low x_{IP}, high β, low z_{IP}
- fair description of data by two gluon exchange models (BJLW)
- good description of data by saturation model
- good description by semi-classical model
- satisfactory description by soft colour neutralization models

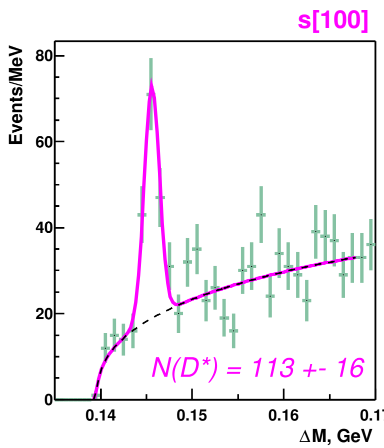
Charm in Diffraction
short term prospects

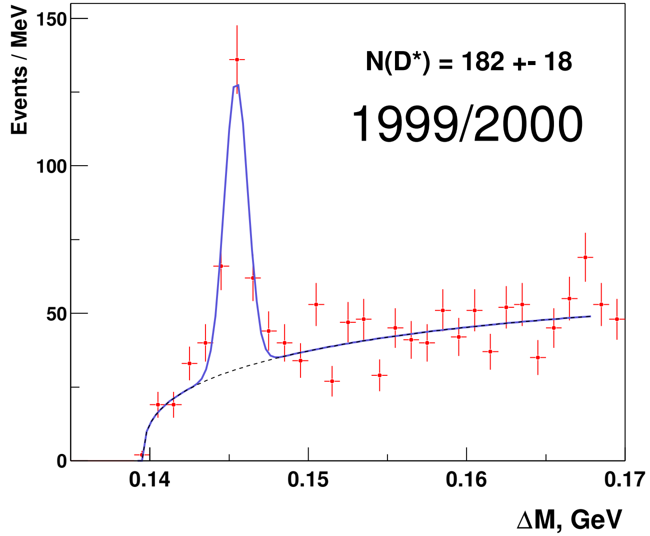
- full HERA I dataset
  - factor 4 in statistics in DIS
  - plus photoproduction and low Q2 analyses









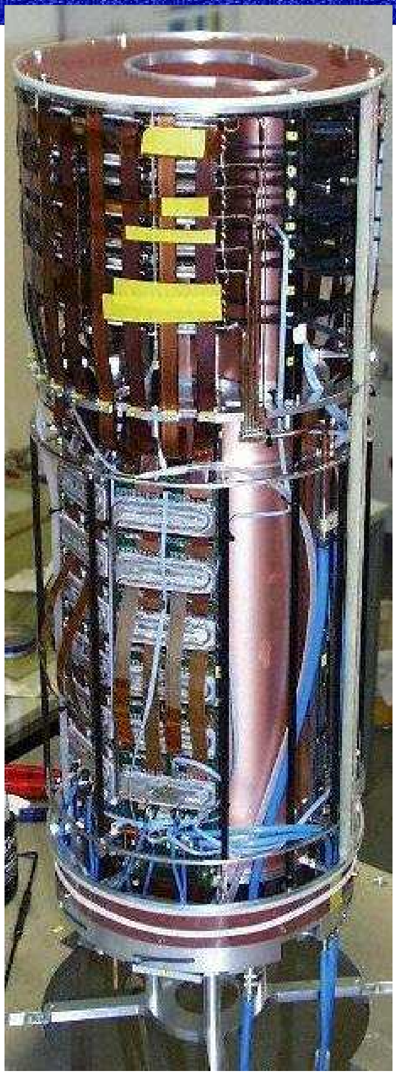


Summary HERA I

- experimental problems
  - measurement in forward (proton) direction
  - triggering charm (low Et processes in general)
- theoretical problems
  - theory uncertainties larger than measurement errors
- statistics limited at HERA I
  - double tags (e.g. D*μ analysis)
  - charm in diffraction (e.g. 250 events in DIS)
- Charm program at HERA I not exhausted yet
- not covered at HERA I
  - charm in charged current interactions (e.g. determine s quark density)

- H1 upgrade projects address these questions ...
- ... and of course a factor (>4) in luminosity will play an important role

H1 @ HERA II



- new detectors
  - FST
  - FTD
  - CIP
  - FTT (Fast Track Trigger)
  - ...
- will all help the charm programme

Conclusions and Outlook

- HERA I has made (and will still to make) substantial contributions to
  - understand the production of charm (and beauty)
  - improve our knowledge about the structure of the proton and the photon
- Uncertainties of theoretical predictions are still very large
  - more precise calculations are very desirable (NNLO, NLO MC, ...)
- Experimental uncertainties typically smaller but still large
- HERA II with its considerable increase in luminosity and the improved H1 detector will allow even deeper insight into these interesting topics of QCD

... and finally

- bright future for Heavy Flavour Physics at HERA
  - improved detectors will allow to access new kinematical regions
  - increased statistics will allow more precise measurements

- a lot of interesting Heavy Flavour Physics can be expected in near future!